In the Specification

Please replace the correspondingly numbered paragraphs with the following substitute paragraphs:

---

a1

[0018] The variable optical attenuators of this application utilize fibers to guide optical signals. The variable optical attenuation in a fiber link is achieved by forming an air gap in the fiber line and by using an actuator-driven blade in the air gap to intercept the optical path in the air gap by optical refraction, optical reflection, or a combination of both. A fiber link in such a VOA has an input fiber and an output fiber that are spaced from each other and are optically aligned relative to each other to allow for efficient, free-space optical coupling from the input fiber to the output fiber without collimating optics between the fibers. When the end facets of the both input and output fibers are substantially perpendicular to the fiber axes, the input and output fibers are aligned to have their optic axes coincide with each other. When at least one fiber has an angled end facet, the alignment of the fibers should be arranged in such a way that the axis of the light launched from the input fiber, which is refracted by the facet of the input fiber, should intercept the center of the core of the output fiber so that the light beam overlaps with the optical axis of the output fiber after refraction by the facet of the output fiber. For example, when facets of input and output fibers have the same angle and are aligned in parallel, the axes of the input and output fibers may be spatially shifted laterally while keeping the fibers parallel to each other. The VOA device may be fabricated with grooves for holding and self-aligning

Concl'd A1

~~of~~ the input and output fibers;~~,~~ the blade and its actuator may be integrated on a suitable substrate, such as a semiconductor, to form a micro electromechanical system (MEMS). The control mechanism for the VOA, including control electronic circuits, may be either integrated on the same substrate or located off the chip on a separate substrate. The input and output fibers may be structured so that the numerical aperture of the output facet of the input fiber substantially matches that of the input facet of the output fiber. The gap between the two end facets is set to be sufficiently small so that the optical coupling from the input fiber to the output fiber is a direct free space coupling through the air gap and the loss of optical coupling is very small in the absence of the intervention of the blade. For example, the optical loss in the direct coupling of single mode fibers is about 0.2 dB and 1 dB for gaps of 30 and 60 microns respectively. In general, the optical loss decreases with the gap and vice versa. Since the gap should be large enough to accommodate free motion of the blade in the gap, the size of the gap may be limited to a range approximately between 10 and 100 microns, or more preferably between about 10 to 50 microns in many designs of the blade.

A2

[0021] When the blade intercepts partially or completely the light from the input fiber, the intercepted part of the light is generally split to three parts by the blade: back reflected light, the refracted light, and ~~multiply-refracted~~ multiply refracted and reflected light. The ~~multiply-refracted~~ multiply refracted and reflected light is much weaker than refracted and reflected light and has larger incident angle and larger lateral shift from the core

of the fibers. Hence, the effects of the multiply refracted and reflected light will be neglected thereafter. The refracted light will have negligible coupling to the output fiber due to its altered incident angle and lateral displacement to the fiber core for a properly-designed blade. Therefore, two basic requirements for the blade of the VOA are to prevent the refracted beam from being forwardly coupled to the output fiber and to eliminate the reflected light from being backwardly coupled into the input fiber. The back reflection and refraction may be decoupled from the fibers if they either are laterally shifted away from the core of the input fiber and output fiber respectively or have an incident angle greater than the maximum incident angle of the input fiber and the output fiber respectively. The sine function of the maximum incident angle is equal to the numerical aperture, NA, of the fiber. The NA for a typical single-mode fiber is about 0.14, which corresponds a maximum incident angle of about 8 degrees.

Concld a2

[0023] An active, closed-loop ~~close loop~~ control mechanism may be implemented to dynamically control the position of the micro blade to maintain the optical power in the output fiber at a desired level by monitoring the optical power in the output fiber. An optical coupler may be formed in the output fiber or attached to the output fiber to split a small fraction of the power in the output fiber as a monitor beam. The monitor beam is fed into an optical detector, which produces an output representing the optical power in the output fiber. An actuator control circuit, coupled to the optical detector and the actuator, is used to adjust the actuator according to the measured

a3

Concld a3

optical power.

a4

[0025] FIG. 1 shows one embodiment of a variable optical attenuator 100 formed on a Si substrate 101 in an integrated package. Two fibers 111 and 112 are laid in a groove fabricated on the substrate 101 to align with each other and are spaced by a gap 114. The groove in the substrate 101 may be a V-shaped groove etched in the single-crystal materials such as Si or other shaped grooves such as a rectangular or U-shaped grooves by using, e.g., a wet etching process or other suitable etching processes. The gap 114 is small so that the spatial spread of the output beam from the fiber 111 due to the beam divergence at the output fiber 112 is negligible and the associated optical loss is small, e.g., less than 0.5dB. A micro blade 120 is engaged to an actuator 150 and positioned to move in the gap 114 in a controlled manner. The micro blade 120 may be formed from ~~a material for~~ the substrate material, such as Si, and has a support arm 122 that engages to the actuator 150 to support and move the blade 120. The input fiber 111 receives an input beam 102. At least a portion of the input beam 102 is coupled through the gap 114 into the output fiber 112 as an output beam 104. As the position of the micro blade 120 varies in intercepting the beam in the gap 114, the power of the output beam 104 varies accordingly.

[0026] An optical splitter 116 is formed or engaged to the output fiber 112 to split a fraction of, e.g., a few percent, of the output beam 104 to produce a monitor beam 108. Fibers may be used to carry the beams 104 and 108. The optical splitter 116 may be implemented in various configurations. For example, a portion of the fiber 112 may be side-polished to remove a portion of the fiber cladding

Cont'd A4

to form an optical port through which the optical energy in the fiber 112 can be evanescently coupled out of the fiber 112 to produce the monitor beam 108. Also, the fiber 112 may be cut to have an output facet at the location of the splitter 116 and a beam splitter 116 may be used to produce the monitor beam 108. In yet another example, an angled fiber Bragg grating may be fabricated in the output fiber 112 so that a small fraction of light is reflected in the direction normal to the optical axis of fiber to produce the monitor beam 108.

A5

[0031] In the embodiments shown in FIGS. 3A through 3D, however, the input and output fibers 111 and 112 are aligned to have their optic axes parallel to each other and are laterally shifted so that their fiber cores 111C and 112C do not face each other. The end facet of each fiber is cut at an acute angle with respect to the fiber core or the optic axis. Hence, the light changes its direction upon entering into or exiting the fiber through the end facet. The propagation direction of the output beam from the fiber 111 is at an angle with respect to the optic axis and directs at the fiber core of the fiber 112 in absence of the intervention by the blade. In such a fiber arrangement, two parallel but slightly ~~laterally-shifted~~ laterally shifted grooves are needed on the substrate 101 to respectively hold the fibers 111 and 112. The advantage of these angle-cut fiber configuration is that the fiber end facets may not necessarily need to be coated with anti-reflective films. In the fiber arrangements shown in FIGS. 2A through 2C, each blade is designed to have a blade surface that faces the input fiber to form an angle with respect to the fiber axes. In FIG. 2A, a blade 210 has a slanted blade surface 210A

a5

facing the input fiber 111. The slanted blade surface 210A forms an angle 216 with respect to the line perpendicular to optical axes of the fibers 111 and 112, where the acute angle 216 may be equal to or greater than half of the maximum incident angle of the fibers, which is about 8 degrees for a typical commercial single-mode fiber. The opposite blade surface 210B is shown to be substantially perpendicular to the axes of the fibers 111 and 112. As illustrated, an output beam 201 from the input fiber 111 propagates towards the fiber core 112C of the fiber 112 in free space. The blade 210, when uncoated and placed in the gap 114, reflects a portion of the beam 201 as a reflected beam 202 by the slanted surface 210A and transmits the other portion of the beam 201 as a transmitted beam 203. The reflected beam 202 directs away from the fiber core 111C due to the angle 216 of the slanted surface 210A to reduce optical back reflection to the fiber 111. Due to the angle of the reflection, even when the reflected beam 202 impinges upon the fiber core 111C of the fiber 111, the coupling can be significantly reduced in comparison with the coupling when the reflected beam is parallel to the fiber core 111C of the fiber 111. Due to the refraction at both surfaces 210A and 210B, the transmitted beam 203 is also directed at an angle with respect to the optic axis of the fiber 112. Therefore, the transmitted portion of <u>the</u> intercepted beam can be decoupled from output fiber and lead to the attenuation if its incident angle to the output fiber is equal to or greater than the maximum incident angle of the output fiber. The position of the blade 210 in the gap 114 between the fibers 111 and 112 can be varied to control the portion of the beam 201 to be intercepted by the blade 210 and hence the optical coupling into the fiber 112. When the

Concld a5

beam 201 is completely intercepted by the blade 210, the coupling to the fiber 112 is minimum, which may be set at zero or a desired low power level. Alternatively, the blade 210 may be coated with a reflective layer on at least the surface 210A to attenuate the beam 201 by reflection. The intercepted portion of the beam 201 is ~~completed~~ completely reflected into the beam 202 without transmission.

a6

[0034] FIG. 3A shows a uncoated blade 310 with a slanted front surface 310A with an angle to the optic axis of the fiber 111 and a back surface 310B that is substantially perpendicular to the optic axis of the fiber 112. This blade design is similar to the blade 210 in FIG. 2A but is used in a ~~laterally-shifted~~ laterally shifted fiber configuration for the angle-cut fibers 111 and 112.

[0035] FIG. 3B shows a transparent or semitransparent blade 320 with both blade surfaces 320A and 320B parallel to each other and perpendicular to the fiber axes of the fibers 111 and 112. The fibers 111 and 112 are in a ~~laterally-shifted~~ laterally shifted fiber arrangement so that the end facet 111A is not parallel to the surface 320A. The angle of the end facet 111A is selected so that the reflected beam 202 is either reflected away from the fiber core 111C to directly increase the optical return loss, or reflected at a sufficient angle relative to the fiber core 111C to reduce the optical coupling back to the fiber 111. The angle of the end facet of each fiber and the thickness of the blade 320 may be selected to produce a lateral shift in the position of the transmitted beam 203 away from the fiber core 112C of the fiber 112 in the transmission mode. If the

front surface of the blade 320 is reflective, the thickness of the blade 320 may be freely selected.

Concld A6

[0036] FIG. 3C shows a variation of the design in FIG. 3A where the blade 310 is optically reflective to attenuate light by reflection. The blade 310 may be formed of a metal or a transparent or partially transparent material but coated with a reflective coating on at least the front blade surface 310A. FIG. 3D shows a variation of the design in FIG. 3B where the front surface 320A or each of the surfaces 320A and 320B of a blade 320 is reflective. Because the thickness of the blade is no longer used to produce a lateral shift in the beam position on the fiber 112, the blade can be made as thin as practically possible to reduce the gap 114 between the fibers 111 and 112. In one implementation, for example, the reflective blade ~~310~~ 320 may be 5 ~~micron~~ microns in thickness to achieve a gap as small as about 15 microns with a spacing of about 5 ~~micron~~ microns on each side of the blade from the end facet 111A or 112A.

A7

[0039] The above direct fiber-to-fiber coupling configurations can be used to eliminate anti-reflective coatings on various optical surfaces such as the slanted blade surfaces in the transmission mode and slanted end facets of the fiber to reduce the manufacturing cost and complexity. When end fiber facets are perpendicular to the optical axis, anti-reflective coatings are highly desirable on facets 111A and 112A to reduce the unwanted back reflection. In addition, the blade designs can be micromachined to reduce the blade thickness to about 10 microns or less to achieve a small gap between fibers for

direct fiber-to-fiber coupling without coupling optics. Furthermore, the input and output fibers 111 and 112 may not be parallel to each other but form an angle between their optical axes where the angles of the end facets of the fibers 111 and 112 and the angle of the front surface of the blade 120 are designed to allow the beam output from the input fiber 111 to be directly coupled through the gap 114 into the fiber 112.

Concld A7

[0040] FIG. 4 shows a cross sectional view of the devices in FIGS. 2A through 3D along lines AA' as shown in FIG. 2A to illustrate the operation of the actuator-driven blade 120 of FIG. 1. The actuator 150 is assumed to be a rotational actuator that rotates the support arm 122 (also of FIG. 1) and the blade 120. The micro blade 120 is shown to be in two positions 401 and 402 due to rotation caused by the actuator 150. The position 402 is closer to the optic axis in the center of the fiber core than the position 401. Hence, the attenuation at the position 402 is higher than that at the position 401. In fact, position 401 is chosen so that light is intercepted by the blade at that position. One advantage of the rotational actuator is that the length of the support arm 122 of the blade 120 may be sufficiently long to amplify the movement of the blade 120. Hence, a small movement at the base of the support arm 122 near the rotational axis causes an amplified movement of the blade 120 at the tip of the support arm 122.

A8

[0043] The movable part 510 includes a movable arm 516 patterned to have movable conductive teeth 518 and the support arm 122 with the micro blade 120. The movable teeth 518 are arranged to spatially interleave with the stationary

A8 teeth 524A and 524B in the stationary part 520 to form an array of capacitors between two adjacent teeth 518 and 524A (or 524B). The movable teeth 518 are set at a common potential that is different from the potential of the stationary teeth 524A and 524B. The potential difference between the potential on the movable teeth 518 and the potential on the stationary teeth 524A and 524B cause an electrostatic torque on the movable structure. Hence, the potential difference can be controlled and varied to control the rotation and therefore the position of the movable teeth 518 and the micro blade 120.

[0044] More specifically, the substrate 101A is fabricated to have two fixed parts 512 and two resilient hinges or springs 514 to rotatably engage the movable arm 516 to the substrate 101A. The hinges 514 may be torsional hinges or bending hinges. In one implementation, each spring 514 may be patterned into a serpentine configuration which has one part attached to the movable arm 516 and another part attached to its respective fixed part 512 to operate as a rotational hinge for the movable arm 516. The two hinges 514 define the rotational axis of the movable arm 516. Alternatively, the serpentine hinges 514 as illustrated in FIG. 5A may be orientated 90 degrees to be serpentine bending hinges. However implemented, in the absence of any electrostatic interaction between the stationary teeth 524A, 524B and movable teeth 518, the torsional forces of the springs 514 keep the movable arm at a position at which the micro blade is outside the gap ~~114~~ 526 between the fibers 111 and 112. At this state, the optical signal from the fiber 111 is completely coupled into the fiber 112 without attenuation (FIG. 5A). When the

Concld A8

potential difference between the teeth 524A, 524B and 518 is controlled to produce an electrostatic force to pull the movable teeth 518 towards the stationary teeth 524A, 524B, the micro blade can intercept the beam between the gap 114 by an amount determined by the potential difference (FIG. 5B).

[0045] In general, the substrates 101 and 101A (FIG. 4) may be formed of a range of ~~solid state~~ solid-state materials. Typically, dielectric materials such as semiconductors and glasses are used. In one implementation, the top and bottom substrates 101 and 101A may be a semiconductor material such as Si that is doped prior to the fabrication to be electrically conductive. The doping may be either n-type or p-type. The semiconductor material may be a single-crystal material or a polycrystalline material. Alternatively, the top and bottom substrates 101 and 101A may be formed of a non-conductive material such as a glass material but are coated with an electrically conductive layer (e.g., a metallic coating). Moreover, the top and bottom substrates 101 and 101A may be formed of an electrically conductive material such as a metal or a polymer material.

[0046] FIG. 1 shows a VOA with only one optical channel in a ~~predefine~~ predefined direction from the input fiber 111 to the output fiber 112. This basic design may be expanded to form more complex VOA devices.

A9

[0051] One technical issue is to set the spacing of the gap 114 (FIG. 1) between the fibers 111 and 112. In general, this may be done by adjusting the positions of the

Cont'd A9

two fibers 111 and 112 with a microscope or other viewing device. When both fibers 111 and 112 are placed in a common groove on the substrate 101, a fiber stop may be fabricated in the groove to simplify the adjustment of the gap 114. Referring back to FIG. 2A, the side wall of the groove may be fabricated to form a protruded feature or a fiber stop 214 at the location where the gap 114 is. This protruded feature 214 has a length equal to the desired spacing between the fibers 111 and 112. Hence, the fibers 111 and 112 may be placed in the groove on the opposite sides of the protruded feature 214 and are pressed against the protruded feature 214 to set the spacing. The dimension of the protrusion feature 214 is sufficiently small to avoid interference with the optical coupling and the movement of the blade 120. FIG. 8C also shows a fiber stop 818 formed at each gap location between two fibers.

[0052] Each of the above electrostatic actuators may need a proper electrical bias to simplify the servo control circuit and to optimize its operation and performance. The displacement of the actuator may vary with the driving voltage in a nonlinear fashion. However, it is discovered that such an actuator usually has a limited operating range within which the response is approximately linear. There are advantages to ~~operate~~ <u>operating</u> the actuator in this linear range to accurately control the position of the blade and to achieve a sensitive control. In addition, a high damping ratio can be achieved. It is discovered that, the actuator may be electrically biased to be within the linear response range.

a10

[0054] The operation modes shown in FIG. 9A - 9D are "constant on" VOA where the VOA is designed to place the blade 120 out of the optical path between the fibers 111 and 112 and thus does not attenuate the light in the absence of the control signal. The VOAs disclosed in this application may also be designed in a "constant off" configuration where the blade is positioned to totally intercept light without the control signal. This may be realized by either applying a bias voltage to force the blade to move to the middle of the light or by a blade mechanically designed to be in the middle position without any bias.

[0055] FIG. 10 shows a typical response of the rotational comb actuator in terms of the blade position as a function of the driving voltage. At low voltage range 1010, the response is nonlinear and is relatively insensitive. At the high voltage range 1030 ~~1230~~, the response is also nonlinear and relatively insensitive. In the middle range 1020, the blade position is relatively linear and sensitive to the driving voltage change. Hence, the driving voltage should be biased to set the actuator in the operating range 1020.

[0056] FIG. 11 shows the frequency responses of the blade with and without the bias voltage for the rotational comb actuator to illustrate another advantage of the biasing. The bias voltage provides a large damping effect so the peak 1120 of the mechanical resonance is much lower than the peak 1110 of the mechanical resonance without the bias voltage.

[0057] FIGS. 12A, 12B, and 12C show an electro-magnetic actuator that may be used as the actuator 150 for the VOA 100 shown in FIG. 1. Similar to the electrostatic

Concld A10

actuators, this electro-magnetic actuator also has a movable part formed on one substrate 1201 as shown in FIG. 12A and a stationary part formed on another substrate 1202 as shown in FIG. 12B. The substrate 1201 is patterned to have a movable membrane 1203 and two spring hinges 1212 to movably engage the membrane 1203 to the other stationary part 1214 of the substrate 1201 for rotation around the rotational axis defined by the hinges 1212. A coil 1210 of conductive wires is formed and fixed to the membrane 1203. The support 122 and the micro blade 120 are fabricated as integral parts ~~part~~ of the movable membrane 1203 and thus move with the coil 1210. The coil 1210 is electrically connected to the surrounding substrate 1214 with conductive leads that run along hinges 1212 to receive a driving current from an external current source. FIG. 12B shows the structures of the bottom substrate 1202. Magnets 1230 are engaged to the substrate 1202 to provide the magnetic field in which the coil 1210 rotates in response to a driving current. A back iron 1220 is also formed on the substrate 1202 to provide the return path of the magnetic field as part of the magnetic circuit. FIG. 12C shows a cross sectional view of the structure 1203 on top substrate 1201 along the line CC' shown in FIG. 12A. A conductive lead 1240 is shown to cross over the wires in the coil 1210 to connect the terminal of the coil 1210 in the center to one hinge 1212 for connecting to the current source. The lead 1240 is separated from the other parts of the coil 1210 by an insulating layer 1242.

A11

[0060] Initially, two substrates 1301 and 1315 of a suitable material, such as Silicon (Si) in this example, are prepared for being processed. Alternatively, the wafer 1301 may be a silicon-on-insulator (SOI) wafer. FIG. 13A-a shows

Cont'd A11

that, the both sides of the substrate 1301 are coated with SiO2 layers 1302 and 1303 by, e.g., an thermal oxidizing process, by sputtering or ion beam deposition. Next, photoresist layers 1304 and 1305 are formed on both top and bottom SiO2 layers 1302 and 1303 and are patterned through a photolithography to form a top patterned mask 1304a through d and a bottom patterned mask 1305 for alignment markers 1305a and separation lines 1305b (FIG. 13A-b). The top patterned mask 1304 has patterns for stationary ~~part~~ parts of the actuator, including areas 1304a, 1304b for two sets of stationary teeth 801B, 802B, areas 1304c for fiber grooves 420 and the trench 818, areas 1304d for forming a void under the hinges 514.

A12

[0062] FIG. 13A-f shows that the top substrate 1315 is bonded to the top surface of the bottom substrate 1301 ~~by~~ using a bonding layer, such as a molecular bonding layer, to adhere one side of the substrate 1315 to the top SiO2 layer 1302. The bulk part of the top substrate 1315 is removed and polished to form a thinner Si layer 1316 of about 50 microns shown in FIG. 13A-g. Next in FIG. 13A-h, a layer 1317 of SiO2 is formed on the top surface of the thin Si layer 1316. A lithographic process is then performed to fabricate a patterned photoresist mask layer 1318 to define structures associated with the movable part of the actuator, including areas 1320, 1319 for movable teeth 801A, 802A, areas 1321 for blade 120 and the support arm 122, etc. Next, the exposed SiO2 areas in the layer 1317 are etched to transform the patterns of the photoresist mask 1318 to the SiO2 layer 1317. These are illustrated in FIG 13B-j. The photoresist mask 1318 is then removed in FIG. 13B-k. Another patterned photoresist mask layer 1330 is formed to

cover all SiO2 areas and areas 1322 for the serpentine hinges 514 (FIG. 13B-l). The exposed Si areas 1322, 1320, 1319 and 1321 on the top surface of the thin Si layer 1317 are etched with the photoresist mask to a depth of about 25 microns to form a structure in FIG. 13B-m. The photoresist mask 1330 is then removed (FIG. 13B-n). This exposes the hinge areas 1322 without photoresist or SiO2 protection. The above steps prepare the structure for the release of the movable parts such as the teeth 801A, 801B, the blade 120 and its support arm 122, the hinges 514, and movable bar 516. After removal of the photoresist mask layer 1330, a Si etching process is subsequently performed to etch through the remaining depth of about 25 microns of the Si areas in FIG. 13B-o. Since the hinges 514 are etched in FIG. 13B-o, hinges 514 of a thickness less than the thickness of layer 1317 will form after the etching is stopped upon etching through the areas 1322. The other movable parts including teeth 801A and 801B, and the blade 120 and the support arm 122 have original thickness of layer 1317, about 50 microns in the direction perpendicular to the substrate 1301 (FIG. 13B-o). Thickness values of hinges and movable teeth can be independently varied over a wide range. Finally, the top SiO2 layer 1317 is removed to form the structure in FIG. 13B-p.

Concld
A12